RMRS Rocky Mountain Remediation Services, L L C
protecting the environment

PROCEDURE

AQUIFER PUMPING TESTS

Procedure No RMRS/OPS PRO 109
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USE CATEGORY 2

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APPENDICES

1 0 PURPOSE

This standard operating procedure (SOP) discusses equipment and procedures that will be used at the Rocky Flats Environmental Technology Site (RFETS) to conduct aquifer pumping tests in driven well points and/or drilled and completed wells This SOP addresses step drawdown and constant rate discharge pumping tests and is based upon information contained in references presented in Section 7 0

2 0 SCOPE

This document which supersedes Procedure No GW 08 constitutes a standard operating procedure (SOP) that applies to all Rocky Mountain Remediation Services (RMRS) personnel and subcontractors conducting aquifer pumping tests at RFETS

An aquifer pumping test is an *in situ* test used to assess hydraulic characteristics representative of the aquifer being tested This is accomplished by stressing a subject aquifer through the removal or addition of water and measuring hydrostatic pressure response Typically a production well is pumped at fractions of full capacity with pumping rates changing in a time step fashion step-drawdown and/or at a constant rate with water levels measured at frequent intervals in the production well and one or more observation wells (Walton 1987) Time-drawdown and distance drawdown data are recorded and used to calculate aquifer characteristics through type-curve matching, straight line matching or inflection point techniques

3 0 REQUIREMENTS

3 1 Personnel Qualifications

Personnel performing these procedures are required to have completed the initial 40 OSHA classroom training that meets Department of Labor Regulation 29 CFR 1910 120(e)(3)(I) and must maintain a current training status by completing the appropriate 8 hour OSHA refresher courses Personnel must also complete and be current on any other site specific training that may be required to perform these activities at RFETS and are required to have a complete understanding of the procedures described within this and other related SOPs

Personnel conducting the aquifer-pumping test will be geologists and/or engineers with backgrounds in hydrology or field technicians with an appropriate amount of applicable experience or on-the-job training under the supervision of other qualified personnel

3 2 Equipment

Aquifer pumping tests will be conducted using an arrangement of equipment that will satisfy the requirements specific to the test conditions The following is a general list of equipment needed to perform aquifer pumping tests

- A reliable power source
- Submersible or suction pump (pumping rates may range from 0 01 gpm to 10 gpm)
- Flow meter
- Borehole flow meter (optional)
- Discharge control equipment
- Water discharge line
- Temporary holding tank
- Pressure transducers
- Data loggers
- Electronic water level indicator
- Time clock or watch with second hand or digital readout of seconds
- Field notebook and/or field forms
- Black waterproof pens
- Appropriate health and safety equipment

Specific equipment and materials requirements will vary with the type of aquifer pumping test being performed. Guidelines presented in SOP RMRS/OPS-PRO 127 General Equipment Decontamination, are to be followed for decontaminating equipment involved in aquifer pumping tests.

4 0 WELL INSTALLATION AND DEVELOPMENT

All wells should be installed per guidelines in SOP RMRS/OPS PRO 118 Monitoring Wells and Piezometer Installation except for specific design requirements as set forth in this SOP Newly installed wells will be checked for the presence of an immiscible layer prior to well development. The method for detecting these layers in monitoring wells is discussed in SOP RMRS/OPS PRO 105 Water Level Measurements in Wells and Piezometers If an immiscible layer of 5 mm or greater is detected in a newly installed well well development procedures will not continue until the RMRS Project Manager has been notified In the case where an immiscible layer is not identified a water level measurement will be taken according to SOP RMRS/OPS PRO 105 and well development activities will continue The water level measurement along with the total well depth measurement will be used to determine the volume of water in the well casing Well casing calculations are presented in Section 4 1 1 1 of SOP RMRS/OPS PRO 106 Well Development

4 1 Determination of Aquifer Pumping Test Well Location

When selecting a site for an aquifer pumping test consideration will be given to the characteristics of the site as it relates to possible potentiometric surface fluctuations as a result of nearby surface loading (traffic etc) and to the expected gradient of the water table Once a site is selected the criteria shown below will apply

4 1 1 *Aquifer Pumping Test Well Installation*

All pumping wells will be fully penetrating The heterogeneity of the alluvial materials Arapahoe Formation and Laramie Formation at the RFP require that the well screen be strategically placed

4 1 1 1 Well Type

Drilled wells will be constructed according to SOP RMRS/OPS PRO 118 Monitoring Wells and Piezometer Installation Drilled wells will have up to a two foot sump of unscreened casing at the bottom of the well while small diameter push wells (Geoprobe installed) will be completed according to the project work plan specifications The requirement for a sump may be waived in cases where partial penetration of the underlying confining layer may adversely affect the efficiency of the pumped or observation wells (i e upward smearing of clays) or compromise the vertical hydraulic integrity of the confining layer for aquifer testing purposes, as determined by the project hydrogeologist. The base of the well casing will be capped Driven well points may be used for shallow aquifer pumping tests and will be developed according to specifications set forth in this SOP Driven wells may be installed in soft formations free of cobbles and boulders (Harlan and others, 1989)

4 1 1 2 Well Diameter

The well casing diameter will be as small as possible reducing the volume of water in the well, yet large enough to accommodate pumping and measuring equipment.

4 1 1 3 Filter Pack Construction

In wells drilled specifically for aquifer pumping tests, filter pack construction will follow the procedures outlined in SOP RMRS/OPS-PRO 118, Monitoring Wells and Piezometer Installation

4 1 2 *Aquifer Pumping and Observation Well Development*

Well development is the process of removing drilling fluids, sediment and smeared or built-up materials from the borehole walls, filter packs, and/or well screens It also is a process whereby fines within the formation adjacent to the borehole can be removed, thus enhancing well efficiency and allowing the inflow of physically and chemically representative ground water from the formation adjacent to the screened interval of the well This process will be used for all observation and pumping wells, whether they are old wells or newly installed wells

4 1 2 1 Materials and Equipment

The following is a list of well development and associated equipment:

- Mechanical reel equipped with a steel cable,
  submersible or suction pump, pump cables and hoses

- Water quality test kit (pH SC T)
- Wash/Rinse tubs
- Clear plastic sheeting
- Disposable latex or vinyl gloves
- Non phosphate lab grade detergent (e g Liquinox)
- Containers for development water (see SOP RMRS/OPS-PRO 128 Handling of Purge and Development Water)
- Water level probe sufficiently accurate to measure water levels to the nearest 0 01 foot
- Distilled Water
- Field notebook and/or field forms
- Health and safety equipment
- Organic vapor detector (OVD)
- Calculator
- Black waterproof pens

4 1 2 2 Well Development Procedures for Pumping and Observation Wells

Well development for new pumping test wells will be conducted no sooner than 48 hours and no longer than two weeks after installation All aquifer pumping and observation wells new and old, will be developed utilizing a vigorous development method such as surging bailing backwashing, overpumping or equivalent, or any combination thereof Where pumping equipment is utilized, the choice for well development is a submersible or suction pump Surging will be accomplished using a bailer or solid weighted cylinder of suitable length Surge blocks and swabs will be used only when permitted by appropriate well construction and aquifer conditions Drilling or pump installation rig assisted well development may be required for certain well conditions (i e deep wells) and should be addressed during the early planning stages of the well drilling and aquifers test design process

Bailing provides a simple and effective method of simultaneously pumping and surging a well when appropriately applied to well development (Aller et al 1989) The bailer should initially be filled with water raised several feet above the water level and allowed to free fall through the borehole until it strikes the surface of the water and attains full submergence This cycle should be applied repeatedly to surge the well prior to the removal of any water in order to loosen up particulate matter at the well bore face The full bailer should not be allowed to strike the bottom of the well Subsequent bailing will remove the suspended material generated during surging. The procedure should be repeated until the well development criteria of section 4 1.2 3 are met. This well development technique is especially suitable for shallow low yield well applications

Pumping, or overpumping, combined with intermittent surging using a solid cylinder or bailer is generally suitable for wells with higher expected yields and/or greater saturated thicknesses The procedure differs from the bailer method only in that a pump is used instead of a bailer for evacuating groundwater from the capacity bailers or solid cylinders to increase the surging action in wells completed with long saturated screened intervals. Pumping periods and rates will be specified in the field by the project hydrogeologist based on consideration of turbidity levels well yield, and drawdown factors

Backwashing involves alternatively turning a pump on and off to simulate a surging action in the well (EPA, 1987) Backwashing should be conducted at a pumping rate only slightly higher than the well can sustain to avoid clogging the well screen If necessary distilled or deionized water or formation water that has had the sediment removed, will be added to the well bore during the backwashing process to augment the volume of water depleted by periodic pumping to waste The process of backwashing involves raising a column of water almost to the surface shutting off the pump and allowing the water to fall back into the well This process is repeated, starting and stopping the pump as rapidly as possible To minimize the possibility of damaging the pump as a result of sediment locking, the pump should initially be started at reduced capacity and gradually increased The control box should be equipped with a starter lockout to avoid damage to the pump that may result when an attempt to start the pump is made while the pump is backspinning During the backwashing procedure, the well should occasionally be pumped to waste to remove sediment brought into the water column by the surging action (Driscoll, 1986) Backflushing efficiency may be limited by the available pumping equipment and should be used only if an effective surging action can be established in the well

The RMRS project manager will determine whether a pump will be dedicated to a specific well based upon verified organic vapor detector (OVD) readings obtained during the drilling of the well OVD readings are described in SOP FO 15, Photoionization Detectors (PIDs) and Flame Ionization Detectors (FIDs)

Development equipment will be protected from the ground surface with clear plastic sheeting Development equipment will be decontaminated before well development begins and between well sites according to SOP FO 3 General Equipment Decontamination

Decontamination and development water will be handled according to SOP FO 7 Handling of Decontamination Water and Wash Water and SOP FO 5 Handling of Purge and Development Water respectively

4 1 2 3 Development Criteria

The criteria for adequate development of the well will be determined by the project hydrogeologist or engineer and will be approved by the RMRS Project Manager Development criteria set forth in SOP GW 2 Well Development, Section 5 2 1 may be used as guidelines but will not necessarily be binding In addition three consecutive well casing volume readings of pH temperature and specific conductance will be recorded (i e consecutive temperatures that are within 1°C and pH readings that are within 0 2 units) and consecutive conductivity readings fall within 10 percent of each other The calibration and use of these field instruments is described in SOP PRO 108 Measurements of Groundwater Field Parameters

4 2 <u>Procedures</u>

The selection of an aquifer pumping test will be based upon the estimates of hydraulic parameters that are being assessed A test will be selected that will give the desired information while minimizing the complexity and time required to conduct the test

Detailed geologic and hydrogeologic information of the test area will be gathered and synthesized into the aquifer pumping test plan The amount of time available for the test should be considered
Prior to the beginning of any aquifer pumping test, the following must be assessed

- Design of test
- Desired information
- Geologic conditions

- Analytical solution and boundary conditions

4 2 1 *Aquifer Pumping Test Design*

To increase the probability that a proposed test site and associated equipment will yield acceptable results, and to minimize uncertainties in data collection and analysis, the following pumping test design criteria must be evaluated, to the extent that available data allows

- The diameter depth, and position of all intervals open to the aquifer system, as well as total depth

- Radial distance and direction from the production well to each observation well and from any interfering boundary

- Radial distance and direction from any known boundaries to each observation well

- Depth to thickness of and areal and vertical limits of the aquifer system

- The order of magnitude of pertinent aquifer system hydraulic characteristics (Walton, 1987)

It is essential to the success of a pumping test at the RFETS that the relatively low hydraulic conductivities expected to exist in the materials being tested be considered in the design of the pumping test. The low hydraulic conductivities will affect all aspects of the test design, including radius of influence, observation well spacing, pumping rate, length of time to pump well bore storage, duration of the effects of delayed yield, etc In addition, some formations may exist in both confined and unconfined conditions throughout the RFETS site It is likely while conducting a pumping test on such formations at a site which has been characterized as existing under confined conditions, that heads may draw down in the pumping well below the top of the confining layer, causing a change to unconfined conditions If this possibility is suspected, then the test initially should be designed with unconfined conditions in mind. If it is desirable to maintain confined conditions during the test, for example, to do away with the long times potentially required to overcome delayed yield effects and thereby shorten the time required to complete the test, then an injection pumping test should be considered.

The design for a pumping test should begin with the selection of hydraulic parameters that are believed to represent the material being tested This assessment will be obtained from laboratory analyses performed on soil and rock samples representative of the aquifer or by packer tests conducted at or near the proposed test site The design also may be guided by the results of a pretest single hole aquifer test Drawdown in the pumping well will not exceed 25 percent of the saturated thickness if the aquifer is unconfined and will not go below the top of the aquifer if the aquifer is confined

The Thiem equation can be used to determine the pumping rate as follows

Unconfined aquifer

$$Q = \frac{(K\pi)(2Hs\ s^2)}{\ln (R/r_w)}$$

where

R	=	radius of influence (a large number usually greater than 1000 feet, see Bear 1979) (L)
r_w	=	radius of the well (L)
H	=	initial head (L),
s	=	drawdown in the pumping well (L)
K	=	hydraulic conductivity (L/T) and
Q	=	pumping rate (L^3/T)

Confined aquifer

$$Q = \frac{2\pi Kms}{\ln(R/r_w)}$$

where m = thickness of the aquifer

This mav be repeated for a range of hydraulic conductivities to establish a range of possible pumping rates The pumping rates can then be used to design the spacing of the observation wells from the pumping well by assuming various values of r (distance between observation well and the pumping well) and solving for values of s This process can be repeated using various pumping rates The results can then be plotted with r versus s for various values of Q From this graph the optimum pumping rate and observation well spacing can be chosen based on an acceptable minimum drawdown observable in the observation well most distant from the pumping well It is recommended that the minimum observed drawdown for an observation well be at least 0 1 foot

The effects of well bore storage can be significant in low hydraulic conductivity materials To determine the time after pumping begins beyond which well bore storage impacts are negligible, the following equation can be used (Walton, 1987)

$$t_s = 5\,4 \times 10^5 (r_w^2 - r_c^2)/T$$

where	t_s	=	time beyond which effects of storage are negligible (less than 1 percent of drawdown values)(min),
	r_w	=	production well effective radius (ft),
	r_c	=	pump-column pipe radius (ft) and
	T	=	transmissivity (gpd/ft)

At least three observation wells should be installed in the same aquifer as the pumping well and at various distances and directions from the pumping well Observation well spacing will be logarithmic and designed to provide at least one logarithmic cycle of distance-drawdown data (Walton, 1987)

In the event that boundary conditions prevail, observation wells should be spaced along a line through the production well and parallel to the boundary to minimize the effects of the boundary on distance-drawdown data. If boundaries are of interest, it is desirable to space observation wells on a line perpendicular to the boundary and at variable distances and directions from the image well associated with the boundary (Walton, 1987)

The open or screened portions of both the production and observation wells should be open to the same interval of the aquifer unless leaky conditions are anticipated Where leaky conditions are anticipated, at least one aquifer observation well will be open to the same interval of the aquifer as the production well, and one aquitard observation well should be open to the lower portion of the aquitard. Where possible these wells will be fully penetrating

In order to determine the appropriate duration for running a pumping test under water table conditions one of the following equations should be used.

$$t_d = 5\ 4 \times 10^4 m S_y / P_h \text{ (Walton 1962)}$$

where	t_d	=	time after pumping started beyond which delayed gravity yield impacts are negligible (min)
	m	=	aquifer thickness (ft)
	P_h	=	aquifer horizontal hydraulic conductivity (gpd/ft^2) and
	S_y	=	aquifer water table storativity (specific yield) (dimensionless)

or

$$t_i = 5\ 4 \times 10^3 (r^2) S_{aw} / T \text{ (Walton 1987)}$$

where	t_i	=	pumping test duration which must be exceeded if boundary impacts are to be clear (one logarithmic time cycle after impacts become appreciable) (min)
	r	=	distance from observation well to boundary image well (ft)
	S_w	=	aquifer water table storativity (specific yield) (dimensionless) and
	T	=	aquifer transmissivity (gpd/ft)

The equation that gives the greater duration is the equation that should be used

Time intervals for observation well water level measurements vary from short at the start of the test, when water levels decline rapidly to long at the end of the test, when the time rate of drawdown is small A typical range of time intervals for observation well water level measurements are shown in Table PRO 109-1

TABLE PRO 109-1

TIME INTERVALS FOR TIME-DRAWDOWN DATA COLLECTION

Time After Pumping Started	Time Intervals
1 - 2 minutes	10 seconds
2 5 minutes	30 seconds
5 - 15 minutes	1 minute
15 - 50 minutes	5 minutes
50 - 100 minutes	10 minutes
100 - 500 minutes	30 minutes
500 - 1000 minutes	1 hour
1000 -5000 minutes	4 hours
5000 - end	1 day

4 2 2 *Step-Drawdown Tests*

A step-drawdown test (Driscoll 1986) is used to assess well performance under conditions of turbulent flow Also the data obtained from a step-drawdown test can be used to determine the specific capacity of a well This information can be used to select the optimum pumping rate and pump-setting depth for a constant-rate discharge test Transmissivity and storativity values for the aquifer can be assessed from time-drawdown and distance-drawdown graphs plotted from data for the first step and/or for any other step together with data for the preceding steps (Birsoy and Summers, 1980)

Once the pump has been installed in the production well, and the discharge control equipment, flow meter pressure transducers and other previously mentioned equipment have been installed, static water levels at each of the production and observation wells will be collected and recorded. After this has been performed, the data logger will be programmed, pre-test water level data recording initiated, and the test is ready to begin

During a step-drawdown test, the production well will be pumped at several successively higher pumping rates during which time-drawdown data will be collected for each rate, or step Generally, a step-drawdown test should be completed within one day, however, in materials of low hydraulic conductivity, effects due to well bore storage may significantly increase the time required to complete the test The pumping times for each step of the test will be the same (approximately 0 5 to 2 hours in duration) in order to simplify calculations During the performance of these tests between three and eight pumping steps will be used

Electronic pressure transducers and a data logger will be installed in the production well and the observation wells to record time drawdown data during both the pumping and recovery phases of the test In addition hand measurements will be collected as backup data In addition to collection of time-drawdown data, flow rate data also will be collected The information collected during the duration of this test will be recorded on the data sheet provided in Appendix PRO 109A

4 2 3 *Constant-Rate Discharge Tests*

A constant rate discharge test, with one or more observation wells can be used to assess the drawdowns in a well at future times and different discharges the radius of the cone of influence for individual or multiple wells as well as the transmissivity and storativity of the aquifer The pumping rate to be maintained for the duration of the test the pump setting depth and the test duration will be determined prior to commencement of a constant rate discharge test

Once the pump has been installed in the production well the discharge control equipment flow meter pressure transducers and other previously mentioned equipment are installed, static water levels at each of the production and observation wells will be collected and recorded After this has been performed, the data logger will be programmed pre test water level data recording initiated, and the test is ready to begin

The pump being utilized for the pumping test will begin pumping at a previously determined time In order to simplify calculations the time in which the test commences should be on a ten minute interval The data logger will be set to begin collecting data just before or at the same time the pump begins pumping Once the pumping test begins hand collected time-drawdown measurements will begin These measurements should begin at the production well and continue at the observation wells in a pattern that will allow for the most rapid collection of data from well to well The time for collecting hand measurements should follow the times provided in Table PRO 1 as closely as practicable

During the pumping test, the flow meter will be monitored regularly to ensure that a constant flow rate is being maintained. In the event that a constant flow rate is not being maintained, adjustments to the pump power source or discharge control equipment may need to be performed. Flow rates will be monitored at regular time intervals throughout the duration of the test, with the time intervals being small at the beginning of the test. Records of flow rate versus time and time-drawdown data will be maintained throughout the duration of the test.

After completion of the pumping test, recovery data will be collected. The procedures for data collection during the recovery phase of the test will be identical to those preformed during the pumping phase of the test. The information collected during the duration of this test will be recorded on the data sheet provided in Appendix PRO 109A

When the only objective of aquifer testing is to assess the maximum well performance of single wells (i e , average discharge or volume of groundwater produced at maximum drawdown) the step-drawdown test procedure may be modified to conduct a single step, variable discharge, quasi-constant head test. This test will be conducted using a bailer or pump for drawing down the water level to the bottom of the well and sustaining this drawdown by constant pumping or bailing of low-yield wells Water level measurements will be collected at the beginning and end of each pumping cycle or at regular intervals during constant pumping to assure that maximum drawdown conditions are maintained in the well. Discharge will be measured volumetrically using a graduated bucket and stopwatch or an accumulating flow meter, whichever is more appropriate The test duration will be determined in the field by the project hydrogeologist based on well responses and testing objectives The use of an electronic pressure transducer and data logger system for measuring water levels is optional, but generally will be limited to pumped wells only

4 3 Methods of Analysis

For each aquifer pumping test, the analytical solution will be consistent with the conditions at the test site, the information desired, and the test design The project hydrogeologist will be responsible for choosing the analytical method and interpreting the test results. The methods used may include those presented in the published literature presented in Section 6 0

4 3 2 2 Confined Leaky Aquifers

There are many solutions available for leaky confined aquifers (Kruseman and De Ridder 1983) Lohman (1979) discusses the Hantush (1955) and Cooper (1963) method, which does not consider storage in the confining unit, and the Hantush (1960) method which does consider confining unit storage Standard curve matching techniques are used to solve for transmissivity and storativity If confining unit thickness is known the Hantush Jacob (1955) method will yield vertical hydraulic conductivity in the confining unit

4 3 2 3 Unconfined Aquifers

Unconfined aquifers subjected to pumping go through three distinct phases (Freeze and Cherry 1979) During early stages of pumping the response of an unconfined aquifer will resemble that of a confined aquifer due to the expansion of water and compaction of the aquifer The second phase shows the effect of gravity drainage Time drawdown curves will display a decreased slope due to the delayed yield response of unconfined aquifers During the third phase time drawdown curves will again resemble the Theis type curve

The Theis type curve may be used for early and late pumping test data However storage parameters calculated during the early stages of pumping tests may be in the range for that of confined aquifers and must not be used to predict long term drawdowns (Prickett, 1965) Boulton (1963) gives a curve that allows the estimation of the time at which gravity effects are negligible and the Theis type-curve may be used to match late pump test data The storage parameter calculated with this later data can be used to predict long term effects of aquifer pumping (Prickett, 1965)

Boulton (1963) and Prickett (1965) have developed methods of analyzing pumping test data subject to delayed yield Families of delayed yield type curves based upon Boulton s method are available in Lohman (1979) with which standard type-curve matching techniques are used

4 3 2 4 Fractured Rock Aquifers

Available methods for interpreting pumping tests in fractured (fissured) aquifers have been summarized by Gringarten (1982) These pumping test analysis methods are usually based upon solutions for an equivalent porous media aquifer which attempt to relate the actual fractured aquifer behavior to that of a known theoretical model, homogeneous or heterogeneous of lower complexity The double-porosity concept may be applicable to the types of fractured aquifers that may be encountered at the RFETS This concept is a possible analysis tool for fractured aquifers In double-porosity aquifers the fractures and rock matrix blocks form a dual system for transmitting water, with the fractures having a high hydraulic conductivity and low storativity and the rock matrix having a low hydraulic conductivity and high storativity

Both confined and unconfined type-curve models may be used to analyze pumping test data from fractured aquifers For double-porosity analyses, the type curves given by Boulton (1963) for delayed yield are identical to those corresponding to the time-drawdown curves for a confined, double-porosity fractured rock aquifer (Gringarten, 1982) and may be used to analyze the fractured aquifer In this case the fluid released from the fractures occurs first, with the fluid released from the rock matrix appearing as "delayed" yield.

4 3 2 5 Conclusions

For each pumping test performed, the analytical solution will be consistent with the conditions at the test site the information desired, and the test design. The project hydrogeologist will be responsible for choosing the analytical method and interpreting the test results

Many additional methods to analyze aquifer tests are available It is recommended that more than one method be used to analyze each aquifer test. This will allow comparison of values for different methods since no two methods will yield the exact same results To aid in analysis, several commonly used analytical methods have been outlined in Appendix PRO 109B along with the references from which they were obtained. Methods that assume that an aquifer is confined may be used when analyzing unconfined aquifer test data, however corrected drawdowns must be used (Jacob, 1963) A review of the reference should be made before analyzing the pumping test data.

5 0 DOCUMENTATION

Documentation for this SOP will include an aquifer pumping test approval form developed to aid in successful aquifer pumping test design. This form should be completed as a part of the procedure for developing an

Analytical solutions of pumping test results are based upon the type of flow encountered during the test and the type of aquifer being tested This section will first discuss analytical methods for analyzing pumping test data with steady state flow conditions and followed by transient analytical solutions These solutions are further subdivided according to aquifer type

4 3 1 *Steady-State Solutions*

4 3 1 1 Confined/Unconfined Aquifers

The most widely used solution is based upon the Thiem equation (Lohman 1979) Two different forms of the Thiem equation are available One is to be used for confined aquifers and one for unconfined aquifers If the aquifer is unconfined the drawdown should be adjusted using the Jacob (1963) method (Walton 1970)

$$s_a = s_{wt} - (s_{wt})^2/2m$$

where	s_a	=	drawdown that would occur in an equivalent non leaky confined aquifer (ft)
	s_{wt}	=	observed drawdown under water table conditions (ft) and
	m	=	initial saturated thickness of the aquifer (ft)

4 3 2 *Transient Solutions*

Because transient analytical solutions consider aquifer storage the analytical solutions can yield values for specific yield or storativity

4 3 2 1 Confined Non-Leaky Aquifers

Transmissivity and storativity can be determined with the Theis (1935) solution using data drawn from plots of drawdown versus time on log log paper Curve matching techniques with a type-curve (available in Lohman

1979) render values of time (T) dimensionless time (u), drawdown (s), and dimensionless drawdown [W(u) well function of u] which are then used to solve for values of hydraulic parameters. Assumptions for the use of this solution are as follows (Lohman, 1979)

- The aquifer is homogeneous and isotropic·
- The aquifer is infinite in areal extent,
- Water is released from storage instantaneously with decline in head,
- The aquifer is of uniform thickness over the area influenced by the aquifer test;
- The discharging/injecting well maintains a constant discharge rate;
- The discharging/injecting well is fully penetrating, and
- The potentiometric/phreatic surface is horizontal prior to pumping.

Corrections are available to compensate for violations of some of these assumptions (Kruseman and De Ridder, 1983), including corrections for partial penetration, barometric pressure fluctuations, and well-bore storage

The Theis method also can be applied to analyzing recovery data (Jacob, 1963) The solution is derived by using image well theory and superimposing an injection well upon a discharging well A semi-log plot of drawdown versus t/t' (where t = time since pumping began and t' = time since recovery began) yields a straight line through the origin (assuming storage is the same for pumping and recovery) Transmissivity is determined from the slope of the line (Kruseman and De Ridder 1983).

If the value for dimensionless time u, is less than or equal to approximately 0 01, the Cooper and Jacob (1946) straight-line method is valid. A semi-log plot of drawdown versus time yields a straight line for later time values. The slope of the line and its extension to intercept with zero drawdown can be used to solve for transmissivity and storativity respectively

If three or more observation wells have been installed at different directions from the pumping well, and the aquifer is of sufficient homogeneity, then directional hydraulic conductivity may be obtained from the analysis of the time-drawdown data. The directional hydraulic conductivity may be obtained by the method described by Papadopulos (1965) appropriate aquifer pumping test design and is attached as Appendix PRO 109C Once the aquifer pumping test approval form is completed it must be reviewed approved by the RMRS Project Manager prior to the start of the aquifer pumping test

6 0 REFERENCES

6 1 Source References

The following is a list of references reviewed prior to the writing of this procedure

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6 2 Internal References

Related SOPs cross referenced by this SOP are as follows

SOP RMRS/OPS PRO 127 General Equipment Decontamination
SOP RMRS/OPS-PRO 128 Handling of Purge and Development Water
SOP RMRS/OPS PRO 112 Handling of Field Decontamination Water and Field Wash Water
SOP FO 15 Photoionization Detectors (PIDs) and Flame Ionization Detectors (FIDs)
SOP RMRS/OPS-PRO 118 Monitoring Wells and Piezometer Installation
SOP RMRS/OPS PRO 105, Water Level Measurements in Wells and Piezometers
SOP RMRS/OPS-PRO 106 Well Development
SOP RMRS/OPS-PRO 108 Field Measurement of Groundwater Field Parameters
SOP RMRS/OPS PRO 113 Groundwater Sampling

APPENDIX PRO 109A

AQUIFER PUMPING TEST DATA SHEET

Aquifer Pumping Test Data Sheet

Date ______/______/______ Person Recording Data ______________________

Pumping Well No ______________________

Hydrostratigraphic Unit ______________________

Screened Interval __________ft to __________ft

Static Water Level ______________________ft Pumping Well ID ______________________in

Distance to Pumping Well ______________________ft

Test Start Time ________ ________ ________

Time	Name	Tape	Brand	XD	OVA	SC	pH	T	Q	Remarks

Reviewed By ______________________ Date ______________________

Continuation of Aquifer Pumping Test Data Sheet

Pumping Well No. ____________________ **Date** ____________________

Site No ____________________

Crew ____________________

Weather ____________________

Equipment ____________________

Time	Name	Tape	Brand	XD	OVA	SC	pH	T	Q	Remarks

Reviewed By ____________________ **Date** ____________________

Page____**of**____

Aquifer Pumping Test Data Sheet

Date ______/______/______ Person Recording Data ____________________

Observation Well No ____________________

Hydrostratigraphic Unit ____________________

Screened Interval __________ft to __________ft

Static Water Level ____________________ft Pumping Well ID ____________________in

Distance to Pumping Well ____________________ft

Test Start Time ________ ________ ________

Time	Name	Tape	Brand	XD	OVA	SC	pH	T	Q	Remarks

Reviewed By ______________________________ Date ____________________

Continuation of Aquifer Pumping Test Data Sheet

Observation Well No ____________________ **Date** ____________________

Site No ____________________

Crew ____________________

Weather ____________________

Equipment ____________________

Time	Name	Tape	Brand	XD	OVA	SC	pH	T	Q	Remarks

Reviewed By ____________________ Date ____________________

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APPENDIX PRO 109B
AQUIFER PUMPING TEST ANALYSIS FORMS

AQUIFER PUMPING TEST ANALYSIS
THIEM STEADY STATE METHOD

WELL # ______________

HYDROSTRATIGRAPHIC UNIT ________________________

SCREENED INTERVAL _______ ft to _______ ft

Reference Lohman (1979)

Assumptions
- Those listed in reference
- Steady state flow

K = hydraulic conductivity (L/T)

T = transmissivity (L^2/T)

r_1 = distance from pumping well to monitoring well #1 (L)

r_2 = distance from pumping well to monitoring well #2 (L)

h_1 = water level in monitoring well #1 (L)

h_2 = water level in monitoring well #2 (L)

s_1 = drawdown in monitoring well #1 (L)

s_2 = drawdown in monitoring well #2 (L)

b = Aquifer thickness (L)

UNCONFINED AQUIFER.

Q = __________ (L^3/T)

r_1 = __________ (L) r_2 = __________ (L)

h_1 = __________ (L) h_2 = __________ (L)

$$K = \frac{-2.30 * Q * \log_{10}(r_2/r_1)}{\pi(h_2^2 - h_1^2)} = \_\_\_\_\_\_\_\_ \text{ (L/T)}$$

$T = K * b$ = __________________ (L^2/T)

CONFINED AQUIFER.

Q = __________ (L^3/T)

s_1 = __________ (L) s_2 = __________ (L)

r_1 = __________ (L) r_2 = __________ (L)

$$T = \frac{2.30 * Q * \log_{10}(r_2/r_1)}{2\pi(s_1 - s_2)} = \_\_\_\_\_\_\_\_\_\_ \ (L^2/T)$$

$$K = T/b = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \ (L/T)$$

AQUIFER PUMPING TEST ANALYSIS
THEIS CURVE MATCHING METHOD

WELL # ______________
HYDROSTRATIGRAPHIC UNIT ___________________________
SCREENED INTERVAL _______ft to _______ft

Reference Lohman (1979)

Assumptions
- Those listed in reference
- Confined Non-Leaky Aquifer

s = drawdown in monitoring well (L)
t = time since pumping began (T)
r = distance from pumping well to monitoring well (L)
S = storativity (Dimensionless)
T = transmissivity (L^2/T)
u = dimensionless parameter = $r^2S/4*T*t$ (Dimensionless)
W(u) = Well function of u (Dimensionless)

MATCH POINT

Q = ____________ (L^3/T)
u = ____________ (Dimensionless) t = ___________ (T)
W(u) = _________ (Dimensionless) s = ___________ (L)

$T = Q*W(u)/4\pi s$ = ____________ (L^2/T)

$S = 4*T*t*u/r^2$ = ______________ (Dimensionless)

AQUIFER PUMPING TEST ANALYSIS
THEIS RECOVERY METHOD

WELL # ______________
HYDROSTRATIGRAPHIC UNIT ___________________________
SCREENED INTERVAL _______ ft to _______ ft

Reference Kruseman and De Ridder (1983)

Assumptions
- Those listed in reference
- Confined non leaky aquifer
- Coefficient of storage is the same for pumping and recovery

s = drawdown in monitoring well (L)
t = time since pumping began (T)
t = time since recovery began (T)
T = transmissivity (L^2/T)
ds = drawdown over one $\log_{10}$ cycle of t/t' (L)

Q = _________________________ (L^3/T)

T = 2 30*Q/4πds = _____________ (L^2/T)

AQUIFER PUMPING TEST ANALYSIS
COOPER AND JACOB METHOD

WELL # _______________
HYDROSTRATIGRAPHIC UNIT ____________________________
SCREENED INTERVAL _______ ft to _______ ft

Reference Lohman (1979)

Assumptions
- Those listed in reference
- $u \leq 0.01$
- Confined non-leaky aquifer

s = drawdown in monitoring well (L)
ds = change in drawdown for corresponding change in time (L)
t = time since pumping began (T)
dt = change in time for corresponding change in drawdown (T)
t_0 = time at which drawdown is 0 - from extrapolation of straight line through the X intercept (T)
r = distance from pumping well to monitoring well (L)
r_0 = distance from monitoring well at which drawdown is 0 - from extrapolation of straight line through the X intercept (L)
T = transmissivity (L^2/T)
S = storativity (Dimensionless)
u = dimensionless parameter = $r^2S/4*T*t$ (Dimensionless)

r IS CONSTANT

Q = ____________________ (L^3/T)

$T = \dfrac{2.30\,Q}{4\pi ds/d\log_{10}t}$ = _________ (L^2/T) $S = 2.25T(t/r^2)_0$ = ___________ (Dimensionless)

Check $u \leq 0.01$ $u = r^2S/4*T*t$ = ___________ (Dimensionless)

"t" IS CONSTANT

Q = ____________________ (L^3/T)

T = $\frac{2.30\,Q}{2\pi ds/d\log_{10} r}$ = __________ (L^2/T)

S = $2.25T(t/r^2)_0$ = ____________ (Dimensionless)

Check $u \leq 0.01$

$u = r^2S/4*T*t$ = ____________ (Dimensionless)

AQUIFER PUMPING TEST ANALYSIS
COOPER METHOD FOR CONFINED LEAKY AQUIFERS

WELL # ______________
HYDROSTRATIGRAPHIC UNIT __________________________
SCREENED INTERVAL _______ ft to _______ ft

Reference Lohman (1979)

Assumptions
- Those listed in reference
- Confined leaky aquifer

s = drawdown in monitoring well (L)
t = time since pumping began (T)
r = distance from pumping well to monitoring well (L)
S = storativity (Dimensionless)
T = transmissivity (L^2/T)
K' = vertical hydraulic conductivity of confining unit (L/T)
b = thickness of confining unit (L)
u = dimensionless parameter = $r^2S/4*T*t$ (Dimensionless)
v = dimensionless parameter = $r/2(K'/b'T)^{1/2}$ (Dimensionless)
$L(u\ v)$ = Leakance function of u and v (Dimensionless)

MATCH POINT

Q = ______________ (L^3/T)
u = ________________ (Dimensionless) t = ________________ (T)
$L(u,v)$ = ____________ (Dimensionless) s = ________________ (L)
v = ________________ (Dimensionless)

$T = Q*L(u,v)/4\pi s$ = ____________ (L^2/T)
$S = 4T*t*u/r^2$ = ________________ (Dimensionless)
$K = (4v^2b*T/r^2$ = ______________ (L/T)

APPENDIX PRO 109C
AQUIFER PUMPING TEST APPROVAL FORM

AQUIFER PUMPING TEST APPROVAL FORM

PROJECT NO ______________________ DATE ______________________

SUBCONTRACTOR ______________________

GEOLOGIST/ENGINEER ______________________

LOCATION ______________________

HYDROSTRATIGRAPHIC UNIT ____________ TYPE OF AQUIFER ____________

DESCRIPTION OF AQUIFER AND ITS SHAPE ______________________

____

ESTIMATED/ASSUMED HYDRAULIC PARAMETER DESIGN VALUES

K ________ (L/T) Source ______________

K ________ (L/T) Source ______________

S ________ (Dimensionless) Source ______________

Q ________ (L^3/T) Source ______________

Sat. Thickness ______ (L) Source ______________

DEVELOPMENT METHOD ______________________

CRITERIA USED TO DETERMINE WELL IS DEVELOPED ADEQUATELY ______________

	Reading 1	Reading 2	Reading 3
Temperature (°C)	______	______	______
pH (std. units)	______	______	______
Specific Conductance (uS/cm)	______	______	______

ATTACH WELL COMPLETION DATA SHEET FOR PUMPING AND OBSERVATION WELLS

PUMPING RATE ______________________ (L^3/T)

MAXIMUM DISTANCE OF OBSERVATION WELL (0 1 FT DRAWDOWN) ______________ (L)

TIME AFTER WHICH AFFECT OF WELL BORE STORAGE IS NEGLIGIBLE ______________ (T)

DURATION OF EFFECTS OF DELAYED YIELD ______________________ (T)

PARTIAL PENETRATION EFFECTS ______________________

SOLUTION METHOD ______________________

VIOLATIONS OF ASSUMPTIONS ______________________

OTHER ______________________

APPROVED ______________________

RMRS PROJECT MANAGER